EUROPEAN LABORATORY FOR PARTICLE PHYSICS
CERN — AB DEPARTMENT

CERN-AB-Note-2008-003 OP

SPS Machine Protection Tests and Incidents in 2007

J. Wenninger

Abstract

In 2007 the SPS started up with new hardware and software interlock systems for the ring and the extraction lines. The enhanced diagnostics provided by the new systems has been used extensively for tests, day-today operation and incident diagnostics. During the SPS run three machine protection incidents have been recorded with the slow extracted fixed target beam. While two incidents had no direct consequence on accelerator equipment, the third incident resulted in damage to an electrostatic separator. This note summarizes the incidents and the follow up actions that resulted from them.

Geneva, Switzerland
15/01/2008

1. Introduction

The SPS started up in the spring of 2007 with a new interlock system for the ring and the TT20 transfer line [1]. The new system is based on the LHC beam interlock system hardware [2]. The same hardware was already used successfully for the TI8 and CNGS transfer line interlock systems. For the SPS ring 6 Beam Interlock Controller modules (BICs) gather the signals from the interlock system clients and transmit the signals to the SPS beam dumping system [3,4]. The communication between the BICs and the beam dump control electronics is based on an interlock loop with the same design than for the LHC. Contrary to the former SPS interlock system, the new system is configured **NOT** to latch interlocks to avoid cross-talk between beams in the present multi-cycling environment. Latching of repetitive interlocks (for example beam losses) is performed by the new Software Interlock System. Every signal transition in the system is time-stamped with a resolution of 1 microsecond and logged on a cycle basis in the AB logging database.

In addition to a new hardware interlock system, a new Software Interlock System (SIS) was deployed for the entire SPS complex. The old SSIS (SPS Software Interlock System) and its obsolete hardware were not even used as backup. The transition to SIS was very smooth and the SPS profited from the higher flexibility of the new system that allows new simple interlocks to be added within less than 30 minutes if necessary. The number of interlocks managed by SIS has expanded steadily during the 2007 run with over 1200 monitored devices and parameters. The interlock logic ranges from simple tests on values, arrays or string (for states) to complex logic implemented in JAVA classes (for example BLM interlock latching).

This note documents the machine protection tests and 'incidents' that have occurred in the course of the 2007 SPS run. In one case the incident resulted in equipment damage (electrostatic separator ZS1). The complete documentation of the SPS interlock systems for the ring and all the transfer lines (also LHC and CNGS) including a description of all interlock tests and incidents is available on a dedicated WEB site:

https://cern.ch/sps-mp-operation/

2. Machine Protection Tests

The beam interlock system tests for the LHC and CNGS extractions and transfer lines have been repeated (or completed with parts untested in 2006) in 2007. To reduce the manpower resources and test length, an automated interlock test program was developed and carefully tested. This JAVA program is able to automatically test the power converter current interlocks and the interlocks on the BTV screens for the transfer lines. Those two systems require the largest number of repetitive and identical tests due to the large number of equipments (PCs and BTVs), respectively states (BTVs).

With the new ring beam interlock system and its internal diagnostics it became much easier to perform interlock tests for the SPS ring. Among the tests that have been performed, the verification of the main converter interlock is the most interesting and is described below.

2.1. SPS Main Power Converter Interlock Delays

The main SPS power converters (MB, QD, QF1 and QF2) provide interlock signals to the SPS BIS to dump the beam as quickly as possible in the event of a converter failure. The interlock generation delays within the PCs were determined with manually generated converter faults at 14 GeV and 400 GeV. The correlation of the interlock arrival time and of the converter current readout provides an estimate of the interlock delay and of the effect on the beam before the beam is dumped. For all converters the delay is in the range of 7 to 9 ms. For the quadrupole circuits, the current decay at the time when the beam is finally dumped is around 8%. This corresponds to a tune change of more than 2 units. Since the beam crosses two integer and half integer resonances due to the fault, it is very likely that the beam is lost before the arrival of the power converter interlock and that the growing closed orbit r.m.s. around the integer resonance will trigger an interlock due to the excessive beam excursion or due to losses in LSS1, LSS2, LSS4 or LSS6 where the fast BLM systems protect the injection, dump and extraction regions. More details on the test are available in the appended test report.

3. Machine Protection Incidents

Three machine protection incidents have been recorded in 2007. All incidents concern the slow extracted fixed target beam whose protection relies heavily on software interlocks. No incident was recorded during the (short) high intensity CNGS run with 8×10^{17} protons delivered to the CNGS T40 target. No incident occurred during the few interleaved high intensity LHC extractions to the TT40 and TT60 TEDs.

3.1. LSS2 Magnetic Septum (MSE) Incident

The first incident happened during the setting up of the slow extraction with a ‘low’ intensity fixed target beam of 3×10^{12} protons in May 2007. During the setting up an access system interlock (‘chain 11’) stopped the power converter of the LSS2 magnet septum (MSE.218). Because of the strong nominal deflection provided by the septum, the beam was no longer able to exit the septum on its downstream end, but rather hit the septum on the inside. Such a fault was expected to trigger an interlock from the fast Beam Loss Monitors (BLMs) installed all along the extraction channel, but in fact no interlock was triggered and the beam was lost for a number of cycles before the anomaly was detected (during the setting up some of the SIS interlocks had to be masked).

3.1.1. Follow up

1. After the incident, a test was set up to determine the response of the extraction channel BLMs in the event of a total failure of the extraction septum MSE.218. The interlock test report is added at the end of this note. The main outcome was that for such a failure the MSE is only protected by loss monitor SPS.BLM.21905.QDA located at the end of the extraction channel (exit of MSE). The response of this BLM for such a failure is 1 mGray/10^{10} protons.
2. As an outcome of the test, the threshold of that BLM was reduced from 500 mGray down to 100 mGray to ensure that no more than 10^{12} protons are lost before the beam dump is triggered. At the same time the thresholds of all BLMs in the LSS2 extraction channel and the TT20 transfer line were lowered significantly as can be seen from Figure 1 and Figure 2. Furthermore the threshold of SPS.BLM.21905.QDA was interlocked by SIS to ensure that it is never increased beyond 150 mGray.

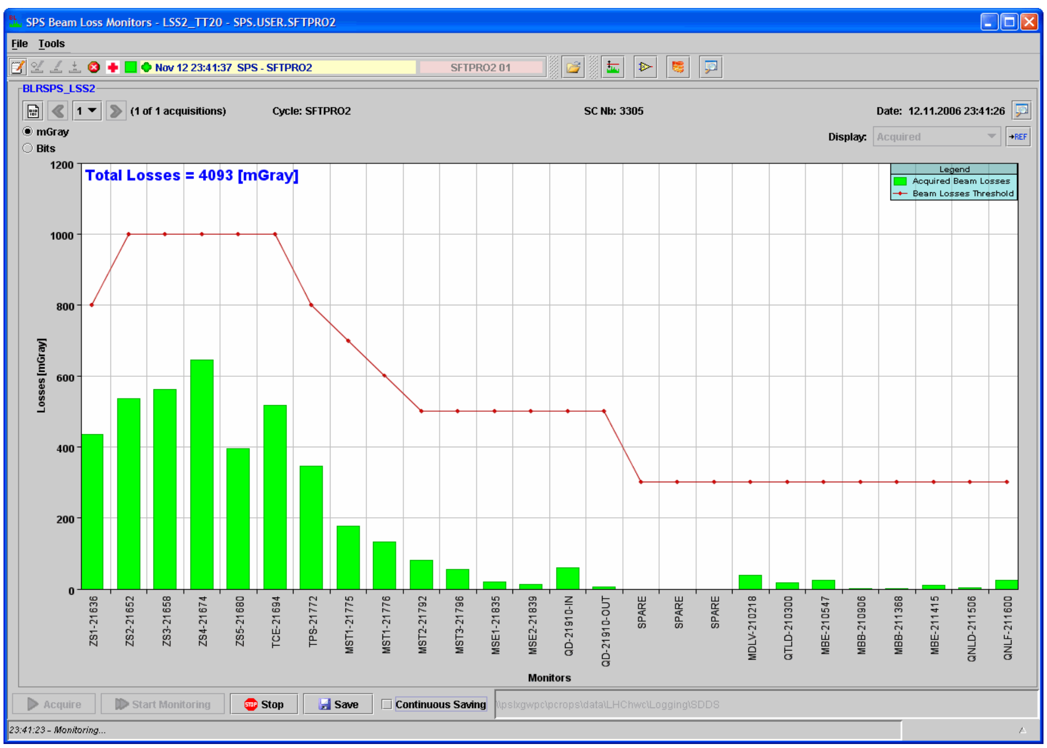


Figure 1 : Beam loss pattern and beam loss thresholds (red line) for the LSS2 extraction channel and the TT20 transfer line in 2006. The losses correspond roughly to 2.5×10^{13} extracted protons.

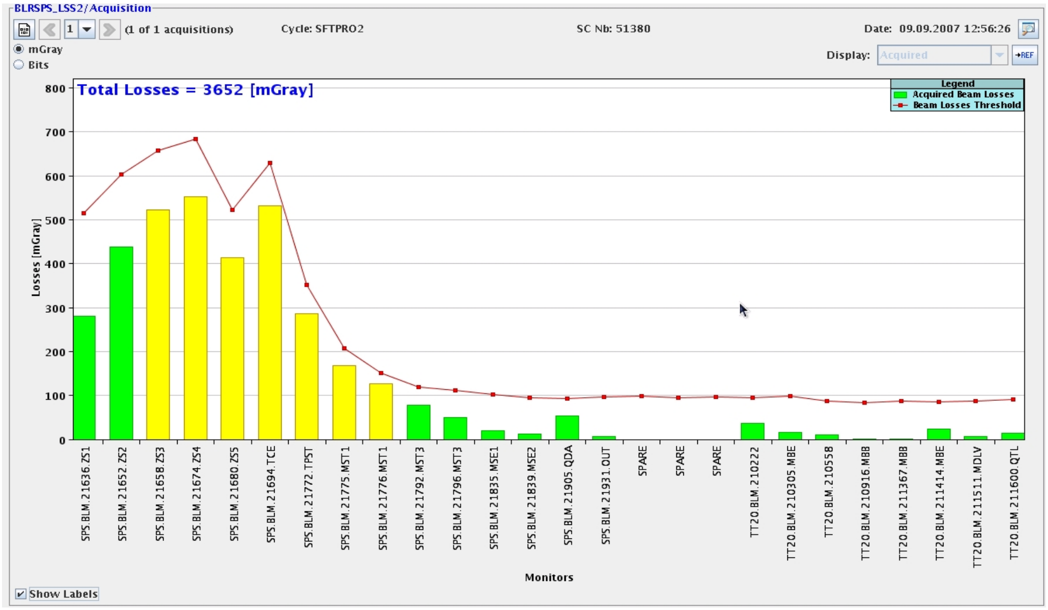


Figure 2 : Beam loss pattern and beam loss thresholds (red line) for the LSS2 extraction channel and the TT20 transfer line in 2007. The losses correspond roughly to 2.5×10^{13} extracted protons. There is a significant reduction of the thresholds with respect to 2006.

3.2. TT20 Dipole String MBE2103 Incident

The second incident occurred in August 2007 in the TT20 transfer line to the North targets in a period where the SPS was switching twice per day (morning and evening) between a short and a long super-cycle.

In the evening of September 4th while the SPS was running with the short night SC, a bad manipulation zeroed the current function of the TT20 main dipole string MBE.2103 on the longer day cycle without being recorded in the SPS parameter trim history (direct HW access). Unfortunately this manipulation was not immediately corrected and the following shift crews were not correctly informed about the problem. When the SPS switched over to the day cycle on September 5th around midday, everything seemed to be normal, except that it was noticed after a few cycles that the intensity readings on the North targets indicated no beam on target although the slow extraction seemed to work normally (SPS page 1 BCT). The TT20 power converter STATE was surveyed by SIS but did not give an interlock since the MBE power converter was indeed ON, but at zero current. Just as the investigations started in CCC to determine the problem the beam was stopped by a vacuum interlock in TT20.

The analysis of the event that is attached at the end of the document revealed that when the MBE dipole strings run at 0 current, the beam is lost inside the dipole string. Beam loss monitors are only installed at the entrance and at the exit of a long string of 9 dipoles, each dipole providing a deflection of 8.8 mrad. No loss is observed by the BLM at the exit of the string because the loss is entirely contained inside the dipole string.

3.2.1. Follow up

1. As an immediate action following this incident, a current surveillance was implemented within SIS for the MBE.2103 converter, the extraction septa MST.217 and MSE.218 as well as the two beam splitter magnets in TCC2. The surveillance worked reasonably well, although it was a frequent source of fake interlocks (which is the reason why is was not implemented before). The implementation is not very robust, since it assumes that the fixed target cycle is the **FIRST** cycle of the super-cycle and the subscription to the power converter data is ‘shaky’. This is largely due to the fact that the SPS power converter control system (ROCS) is still running legacy SL_EQUIP front-end servers.
2. In 2008 a new BLM will be added in front the the TT20 TED which corresponds to the exit of the first three dipoles of the MBE.2103 string. This installation takes advantage of the fact that there is a spare cable available.

3.3. Electrostatic Separator ZS1 Incident

The most severe incident that led to damage of the ZS1 electrostatic separator occurred 3 days before the end of the 2007 SPS run during a test of a new slow extraction scheme.

In 2007 the SPS was still running a slow extraction scheme based on the so-called 'Qsplit' optics for simultaneous extraction to the West and North areas. This requires a change of the phase advance between LSS6 and LSS2 to ensure that the number of betatron oscillations between the extraction points is an integer multiple of 2π. For that reason the F quadrupole family of the SPS is split into two independently powered circuits. Since the dismantling of the West area this extraction scheme base on 'Qsplit' is no longer required and a simpler scheme was optimized by M. Gyr (AB/BT) in the summer of 2007. This simpler scheme liberates one of the main quadrupole converters of the SPS. The test of the new extraction scheme with beam was finally scheduled for the last weekend of the SPS run. The test was scheduled to start after a long SPS MD, first by establishing a good baseline with the Qsplit optics, and then by changing the settings to the new scheme. This scenario implied that the control system knobs of the old extraction had to be zeroed and replaced by the new knobs (for the extraction bumper, the extraction septa, the extraction sextupoles and the TT20 transfer line).

On the evening before the test, the control system 'knobs' were tested: the Qsplit knobs were removed and the new knobs set to their nominal values. After the test the new knobs were zeroed again and the Qplit knobs restored. Unfortunately during the reversal procedure, the extraction bump knob of the new scheme was left on together with the Qsplit bump, resulting in a total extraction bump of over 100 mm. Unfortunately this error was not detected by the control system because the extraction bumper magnets are so strong that it is indeed to possible to produce a bump with twice the nominal amplitude at 400 GeV/c. The reason for the knob test was that the expert for the control knob (the author of this document) could not be present for the beginning of the test.

In the morning of November 9th the SPS switched back to the supercycle for the slow extraction test. The first beam was only extracted at12:20 local time due to various technical problems. One batch of 10^{13} protons was used to verify the slow extraction for the Qsplit scheme. Because of the 'double bump' the beam was swept over the electrostatic separator (ZS) electrodes and into the extraction channel and TT2- line over a few milliseconds during the ramp (not unlike a fast-slow extraction). The dump was triggered by loss monitor TT20.BLM.210222 at the beginning of TT20. The losses in the extraction channel itself where not sufficient to trigger BLMs. Unfortunately the BLM that triggered was of the slower BLRING type (20 ms sampling) and the loss largely exceeded the thresholds when the dump was finally triggered. Two such extractions occurred in consecutive cycles before the ZS system failed and SIS stopped all beams. More details can be found in the appended incident report.

Following the incident the settings of the extraction bumps were fixed and the new extraction scheme was set up successfully. The intensity was however limited because of a high spark rate of the first ZS tank (ZS1). According to the BT experts ZS1 is damaged (wires broken). It will be replaced during the SPS shutdown.

3.3.1. Follow up (2008)

1. Loss monitor TT20.BLM.210222 that triggered the dump for that failure and that is very sensitive because it is installed close to an aperture limitation will be connected to the fast BLD system (μs reaction time) since there is a spare channel available.
2. The current of the extraction bumpers will be surveyed by SIS.
3. Strengths and currents of all SPS extraction bumpers will be limited by software within the LSA trim engine to limit the extraction bump amplitudes to 120% of their nominal values.

4. Summary

In 2007 three machine protection incidents were related to the slow extracted fixed target beam. This is not entirely surprising since the protection of the LSS2 extraction and the TT20 transfer line is not 'very safe'. With the exception of the BLMs, all interlocks for the slow extraction are based on software (SIS) which is intrinsically slow (delay of one cycle). No detailed simulations of failure scenarios have been performed, and most improvements of the protection (for example BLM optimizations) are done following incidents. The possibilities of SIS to monitor more closely the PCs are limited by acquisition issues due to the legacy software within the ROCS control system. A major improvement may be obtained with a proper FESA implementation of the PC control system, or by a dedicated hardware interlock on the PC currents similar to what is done for the LHC and CNGS transfer lines. Unfortunately it is not possible for technical reason to re-use the LHC/CNGS PC interlocking scheme directly.

5. References

1. R. Giachino et al, *Architecture of the SPS Beam and Extraction Interlock Systems*, **CERN-AB-2003-010**.
2. B. Puccio et al, *The beam interlock system for the LHC*, **LHC-CIB-ES-0001**, EDMS No. 567256.
3. B. Todd, *CIBU: Realization of the beam interlock system user interface*, AB Note in preparation.
4. B. Todd et al., *User Interface to Beam Interlock System*, AB Note in preparation.

HW Interlock Test Sheet

EQUIPMENT TYPE	SPS Main Power Conveters
INTERLOCK TEST	Fast Interlock delay
DATE	04.04.2007
RESPONSIBLE	J. Wenninger

TEST CONDITIONS

SPS CYCLE	SFT+MD (16.8 s)
SPS TIMING USER	SFTPRO1
BEAM TYPE	No beam
BEAM INTENSITY	---

Test description

The delay between the occurrence of a fault on the MPS of the SPS and the time of the BIS dump trigger has been determined using the current measurement system of the MPS and the BIC history buffer. 4 test have been performed for:

- The main bends (MB) at 14 and 400 GeV/c.
- The QD and the QF1 at 14 GeV/c.

The results for the delay of the interlock with respect to the moment where the current starts to decay and for the relative current change at the time of the interlock reception (which corresponds within a few ten's of microseconds also to the beam dump time) are given in the table below.

The delay is for all circuits in the range of 7-9 ms.

The current decay of the MB circuit correspond to a maximum orbit shift of 4 (m) × 0.007 = 28 mm which is still within the machine aperture. The SPS momentum aperture is around 1%. The associated tune change is $\Delta Q = -33 \times 0.007 = 0.23$. For the fixed target beam with a tune around 26.6 this is not a problem. For the LHC beam on the other hand, where Q = (26.13/26.18) the tune will shift down and cross the integer tune resonance where the closed orbit becomes unstable and the beam moves towards the vacuum chamber.

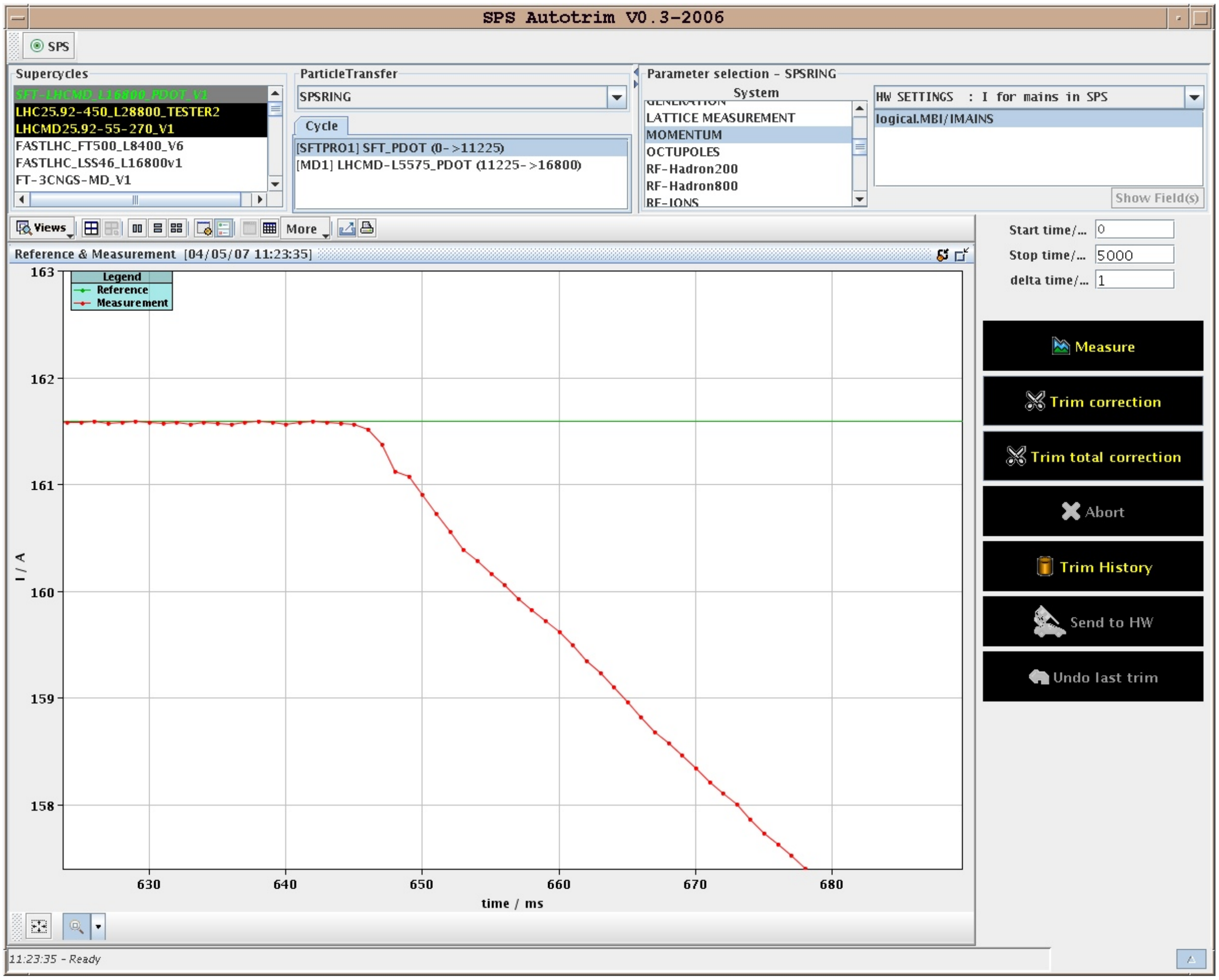
The tune change associated to the 8% current decays of the quadrupoles is $\approx 0.08 \times 26 = 2.1$, which is huge. Both tunes will move towards and cross the integer resonance where the closed orbit becomes unstable and the beam moves towards the vacuum chamber.

The result highly the critical role of the beam position interlock installed in LSS1 on BPH.120 and BPH.122. This system must protect the SPS against such MPS failures.

Circuit	Momentum (GeV/c)	Delay (ms)	Relative current decay (%)
MB	14	7-8	0.7
MB	400	7	0.5
QD	14	8-9	8.3
QF1	14	8	8.1

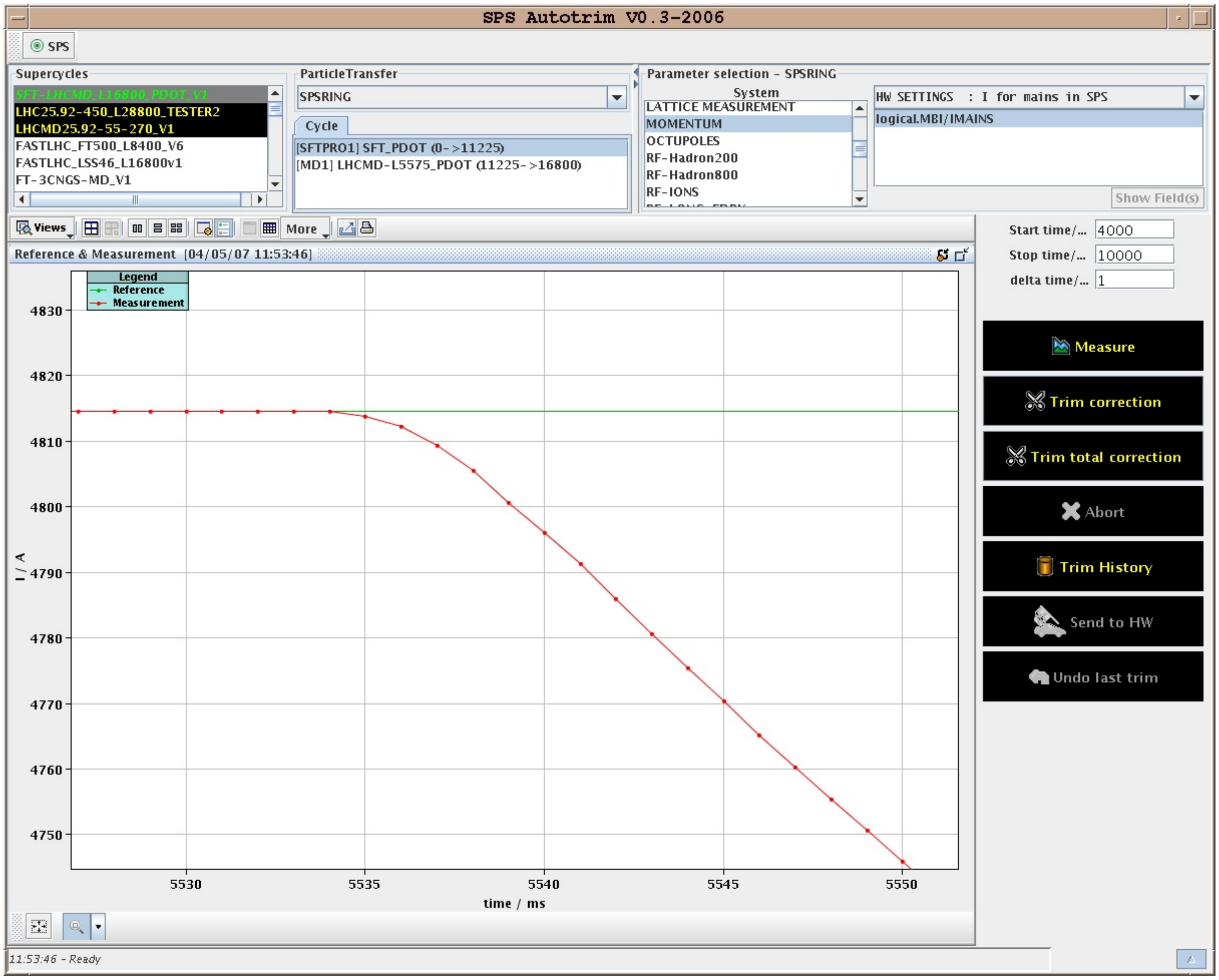
MB test at 14 GeV/c

The BIS detected the interlock at cycle time 653 ms. The corresponding MB current is 160.4 (A), for a nominal current of 161.5 (A). The relative current drop is 0.7%. The time delay is approximately 7-8 ms.



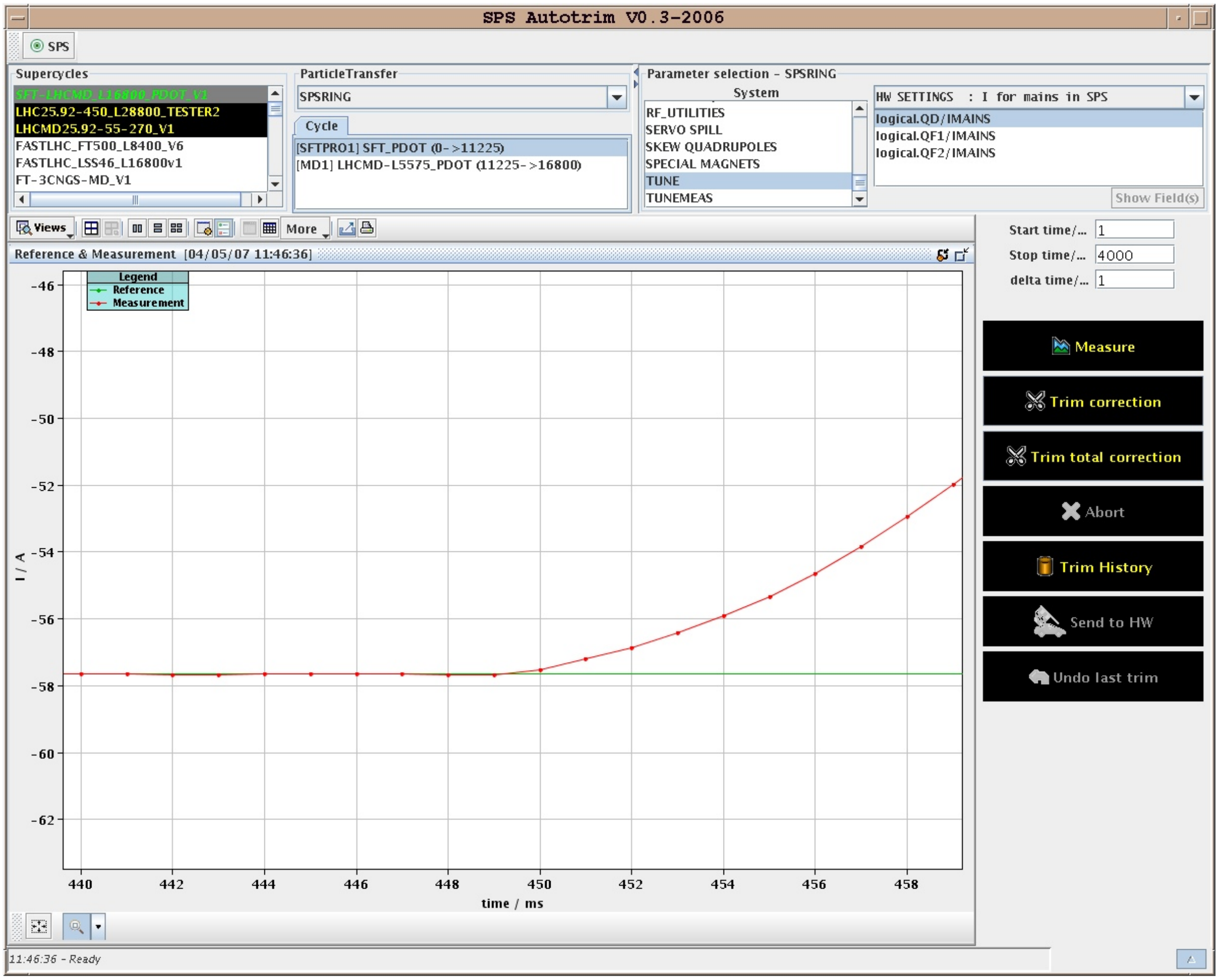
MB test at 400 GeV/c

The BIS detected the interlock at cycle time 5541 ms. The corresponding MB current is 4791 (A), for a nominal current of 4815 (A). The relative current drop is 0.5%. The time delay is approximately 7 ms.



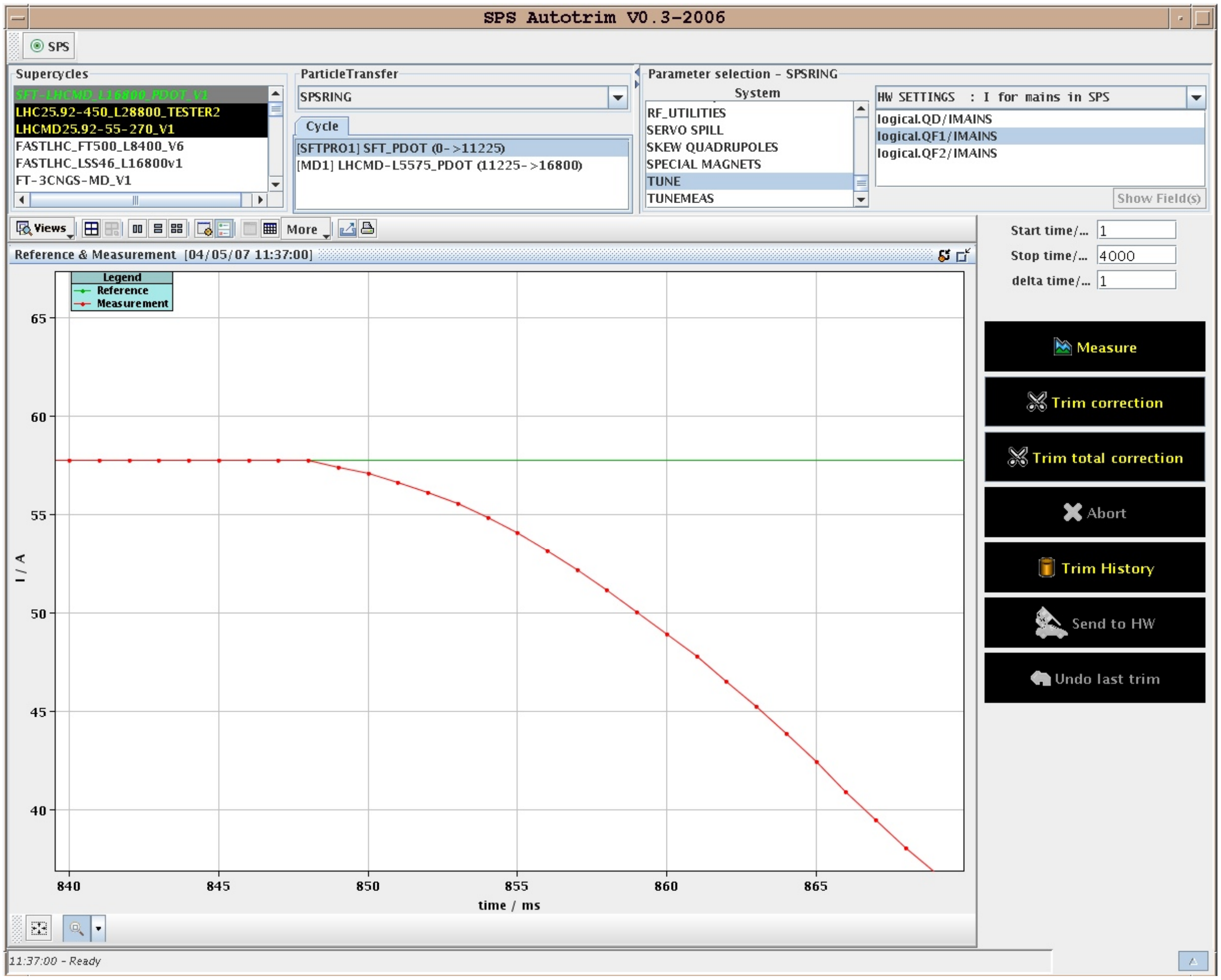
QD test at 14 GeV/c

The BIS detected the interlock at cycle time 458 ms. The corresponding QD current is -53 (A), and the nominal QD current is -57.8 (A). The relative current drop is 8.3%. The time delay is approximately 8-9 ms.



QF1 test at 14 GeV/c

The BIS detected the interlock at cycle time 856 ms. The corresponding QF1current is 53.2 (A), and the nominal QF1 current is 57.7 (A). The relative current drop is 8.1%. The time delay is approximately 8 ms.



HW Interlock Test Sheet

EQUIPMENT TYPE	MSE218 and BLM LSS2/TT20
INTERLOCK TEST	MSE fault – beam hitting MSE
DATE	15.05.2007
RESPONSIBLE	J. Wenninger

TEST CONDITIONS

SPS CYCLE	SFT+MD (16.8 s)
SPS TIMING USER	SFTPRO1
BEAM TYPE	FT
BEAM INTENSITY	3×10^{12} protons / 1 batch

Test description

The aim of the test was to verify the BLM trigger when the beam is hitting the MSE in the North due to a septum trip (for example access chain problem…). The Software Interlock System (SIS) can only check the state of the MSE once per cycle (at the end) and may miss one cycle where the beam is extracted with the MSE OFF.

The slow extraction was tuned to ensure that only 10^{12} protons were extracted during the spill. The thresholds on the BLMs after the MSE were set to 30 mGray. The MSE218 was then tripped on purpose during the MD segment to ensure that the MSE is OFF during the slow extraction. The BLMs triggered a beam dump during the extraction. 2.7×10^{11} protons were extracted before the BLM dump around cycle time 6100 ms, as can be seen on the BCT data shown below.

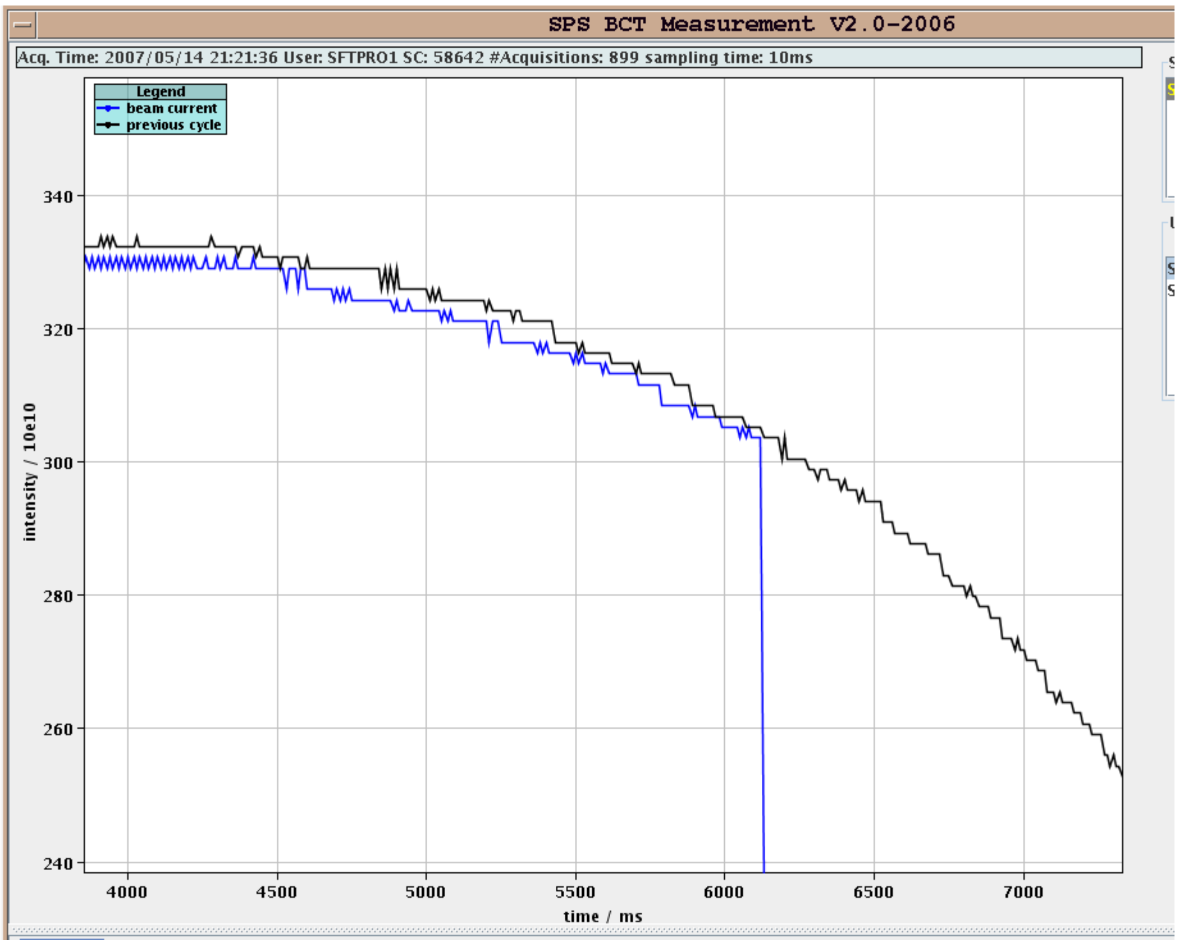


Figure 1 : BCT reading in the SPS ring for the extraction before the MSE trip (black) and during the cycle with MSE OFF (blue). The beam is dumped by the LSS2 BLMs at cycle time ~ 6100 ms.

The evolution of the beam loss through the cycle with MSE off is shown in the following in Figure 2. The loss is well correlated with the slow extraction. The 30 mGray threshold is ONLY REACHED on BLM.21905 that is installed near QDA.219. No significant loss is observed on any other fast extraction BLM. The reason is that there is no other BLM after the seconds MSE magnet, and the other (TT20) BLMs seem to be too far away. The **protection of the MSE in such an event relies therefore on a SINGLE BLM!**

The sensitivity of the BLM for such an event is ≈ 10^{10} protons/mGray.

As a consequence the threshold of that BLM must not exceed 200 mGray to limit the maximum beam loss to 2×10^{12} protons per cycle.

In 2006 the operational threshold at high intensity was set to 500 mGray, which corresponds to a loss of $\approx 5\times10^{12}$ which is still acceptable.

The fact that the protection of such a critical element, installed in a high radiation area, depends essentially on a single BLM suggests implementing a fast current/state surveillance of the MSE and MST. An extension of the FEI (Fast Extraction Interlock) that is implemented within the ROCS system for the surveillance of the fast extractions should be considered. This requires a modification of the interlock logic for the slow extraction and a hardware connection (CIBU interface and cable) to the BA2 Beam Interlock Controller (CIB.BA2.S2).

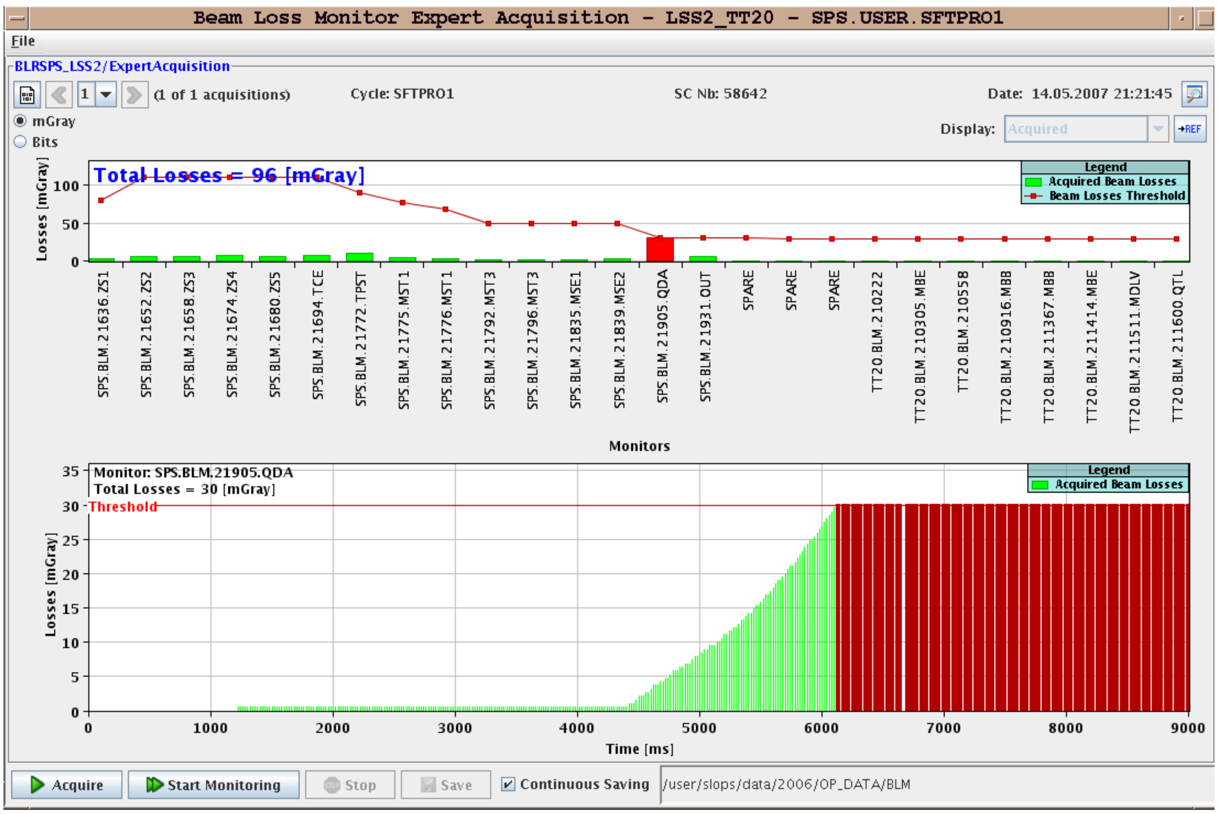


Figure 2 : Evolution of the beam loss with the MSE switched OFF.

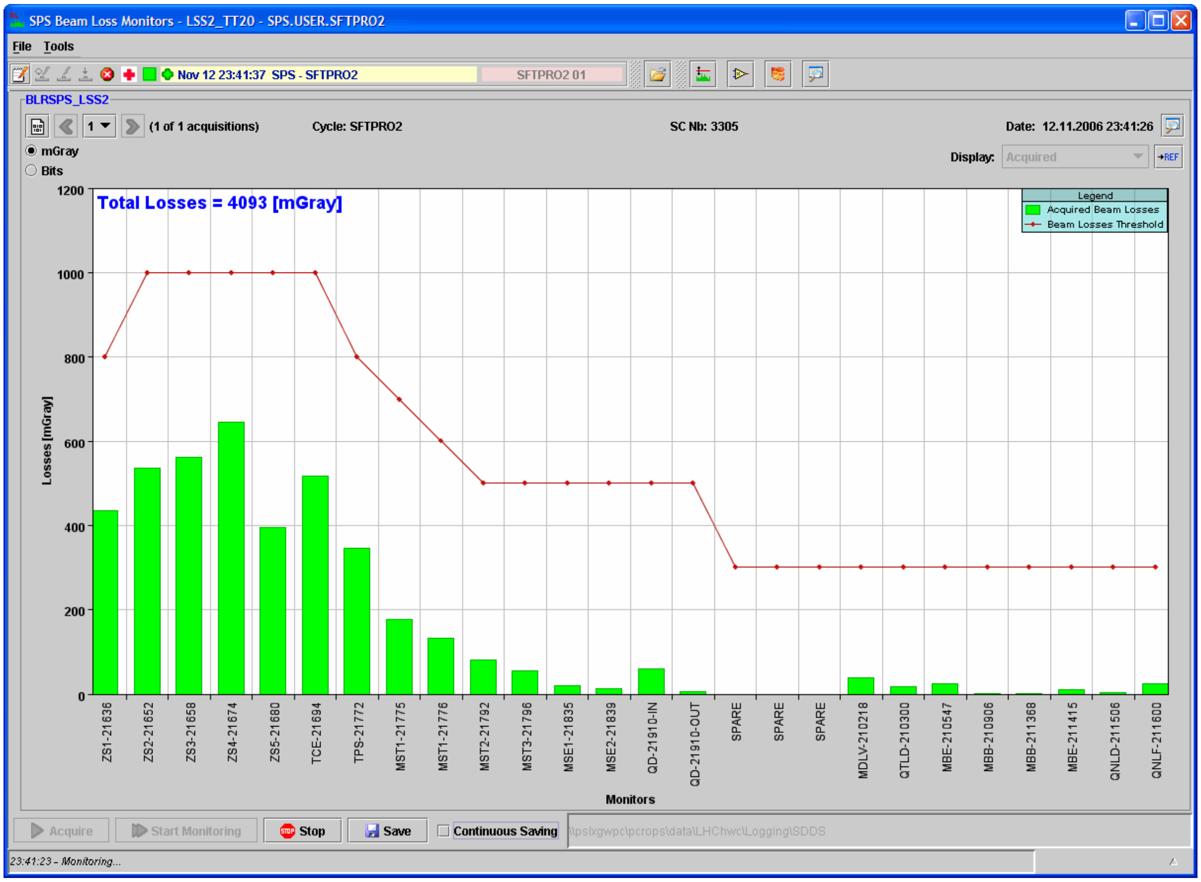


Figure 3 : Operational thresholds and typical steady state losses in LSS2 and TT20 in 2006.

HW Interlock Test Sheet

EQUIPMENT TYPE	MBE2103M and TT20 BLMs
INTERLOCK EVENT	MBE ON but at 0 A – beam hitting MBE magnets
DATE	05.09.2007 12:30
ANALYSIS	J. Wenninger

BEAM CONDITIONS

SPS CYCLE	SFT+LHCION (16.8 s)
SPS TIMING USER	SFTPRO1
BEAM TYPE	FT
BEAM INTENSITY	2.6×10^{13} protons / 2 batches

Event description

Following a manipulation error with the 'EquipState' program, the ZERO-FUNCTION command was executed on the MBE2103M converter of TT20 while the SFTPRO1 cycle was resident but NOT active (evening of 4th September). The next day, this cycle was made active around 12:00 AM, after a change of the beam energy in the PS. The beam energy change was made with the short 14.4 second 'night' cycle (SFTPRO2) during the morning, and the changes were copied to the SFTPRO1 cycle. The beam was immediately accelerated and extracted, but it was noticed that the intensities on target were 0. The shift crew was not aware that the setting of the MBE and of the bypass converters were at 0 A! As the conditions were checked, the TT20 vacuum valves closed. Shortly later the LSS2 vacuum valves also closed. The BIC history recordings are shown in Figure 3 and Figure 4. One TT20 valve was blocked (no communication) after the incident and a reset by the vacuum piquet was required. Fortunately there was no vacuum leak.

The beam losses during that incident were investigated from the logging. The losses of the first two BLMs are shown in Figure 1. 12 complete beams were lost before the valves closed. Only the second BLM recorded a marginal increase of 15 mGray, while the interlock thresholds are 100 mGray (and cannot easily be reduced!). The typical loss pattern and thresholds for LSS2 and TT20 are shown in Figure 2. It is interesting to note that this BLM (210305) is installed at the ENTRANCE of the FIRST MBE magnet. The loss must be due to backscattered particles, or be unrelated to the incident itself. The next BLM at position 210558 is located after 13 MBE dipoles (each deflects the beam by an angle of ~8.8 mrad and is 6 m long): it is clear that this BLM is much too far downstream to be sensitive to such a failure case. The beam is lost entirely between BLMs 210305 and 210558.

The (dramatic) conclusion is that the TT20 line is not protected in case the settings of the MBE are zero or very far from their nominal values. A solution based on FEI (in 2008) or on SIS should be investigated asap!

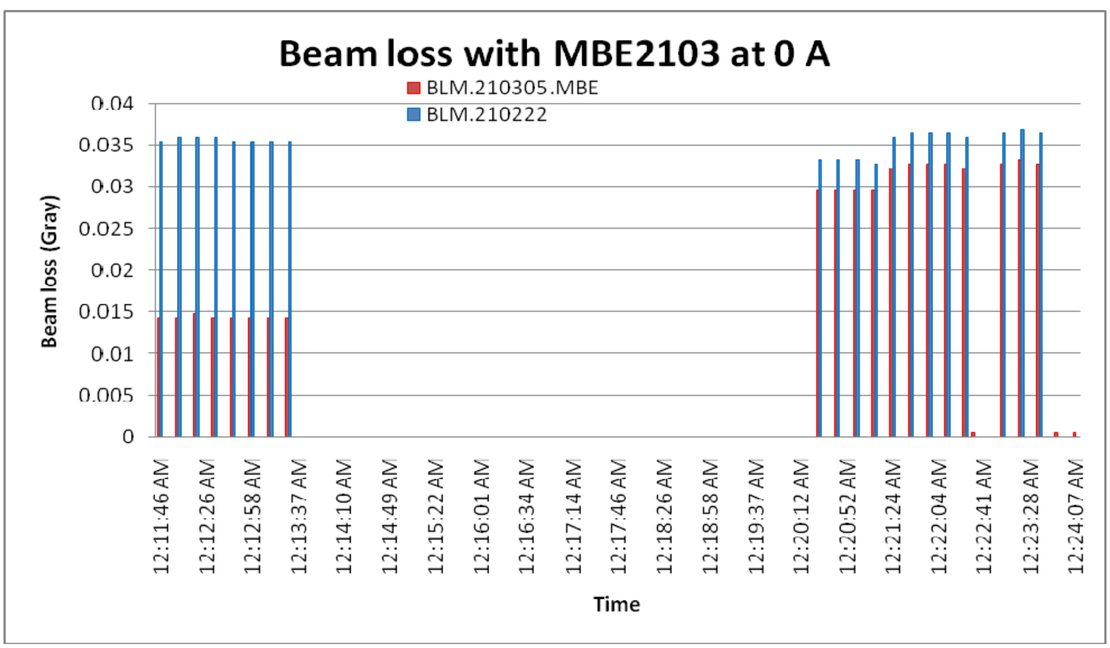


Figure 1 : Readings of the 2 first BLMs in TT20 during the MBE2103M incident. The first monitor remains stable, while the second monitor doubles its losses following the cycle change at 12:20 AM. BLMs further downstream record no losses. The interlock thresholds of those BLMs are 0.1 Gray. Please note that the time axis is off by 7 minutes. The last BLM recording (> 0.03 mGray) correspond to 12:30:33.

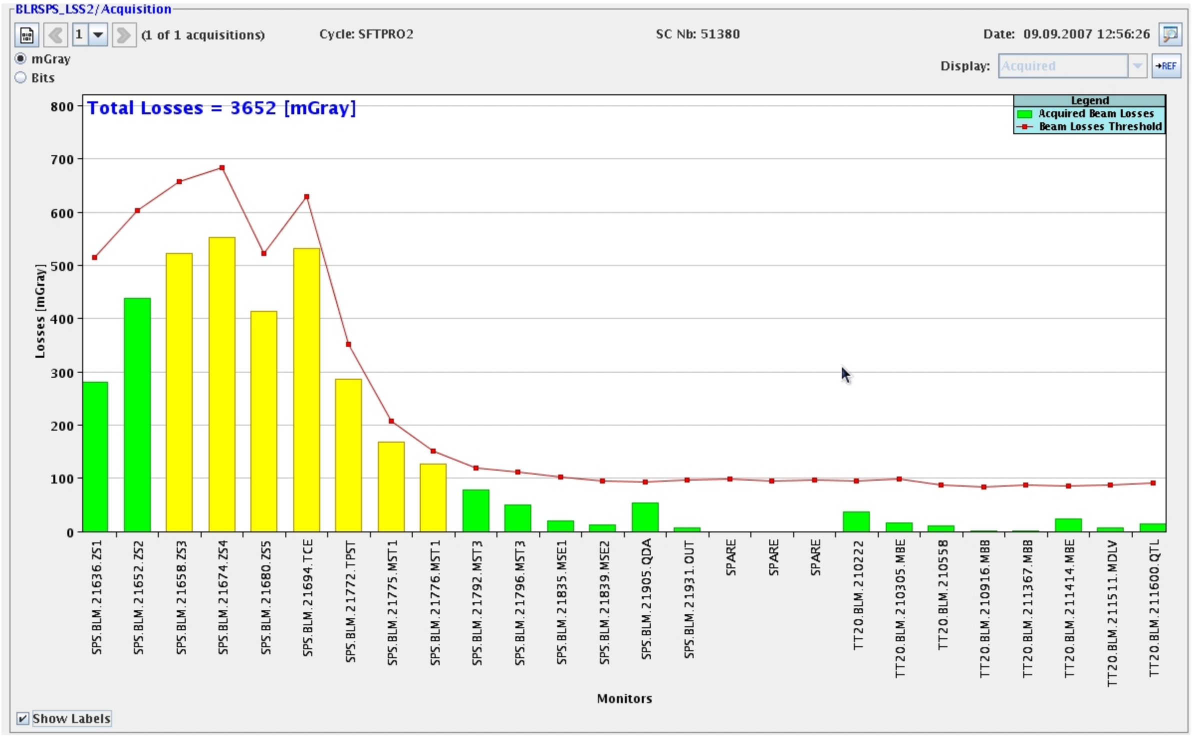
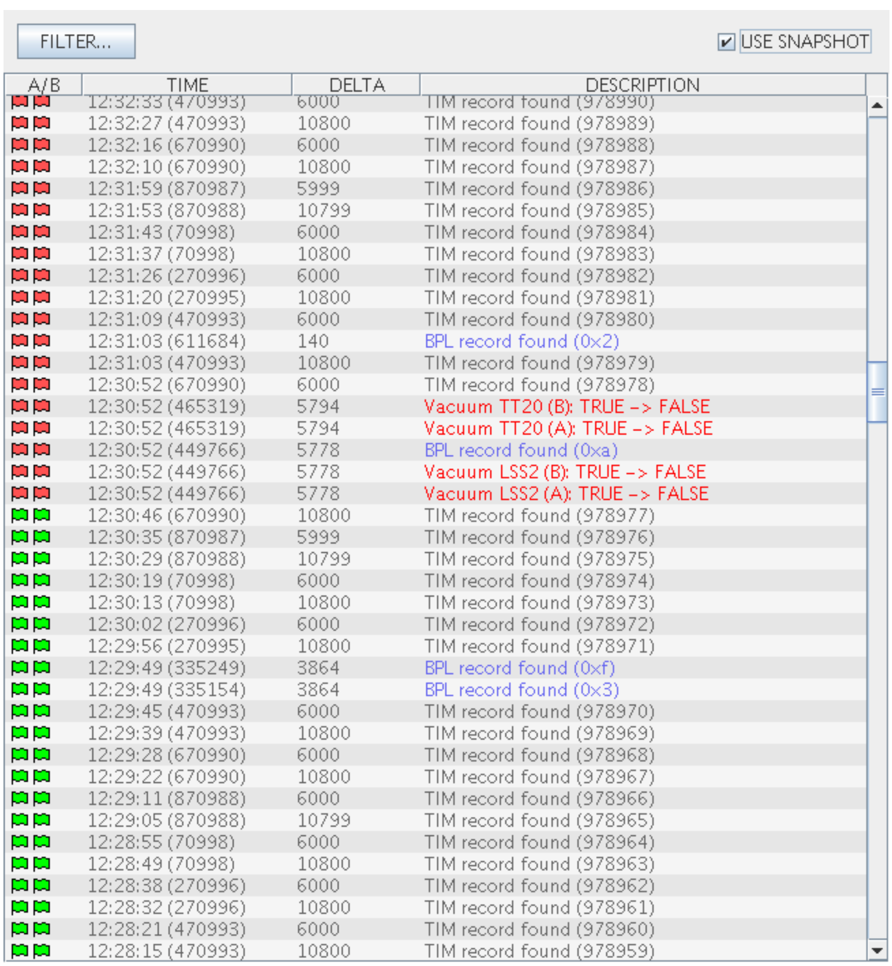
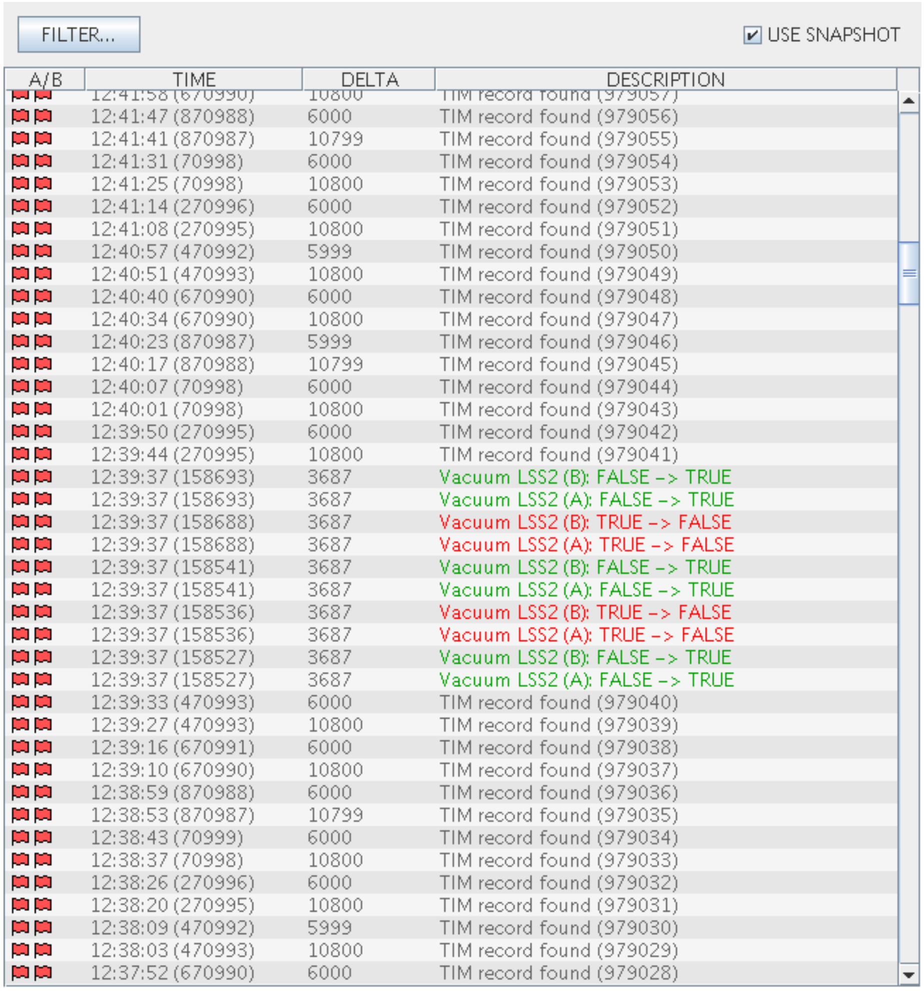


Figure 2 : Operational thresholds and typical steady state losses in LSS2 and TT20 in 2007.



A/B	TIME	DELTA	DESCRIPTION
	12:32:33 (470993)	6000	TIM record found (978990)
	12:32:27 (470993)	10800	TIM record found (978989)
	12:32:16 (670990)	6000	TIM record found (978988)
	12:32:10 (670990)	10800	TIM record found (978987)
	12:31:59 (870987)	5999	TIM record found (978986)
	12:31:53 (870988)	10799	TIM record found (978985)
	12:31:43 (70998)	6000	TIM record found (978984)
	12:31:37 (70998)	10800	TIM record found (978983)
	12:31:26 (270996)	6000	TIM record found (978982)
	12:31:20 (270995)	10800	TIM record found (978981)
	12:31:09 (470993)	6000	TIM record found (978980)
	12:31:03 (611684)	140	BPL record found (0x2)
	12:31:03 (470993)	10800	TIM record found (978979)
	12:30:52 (670990)	6000	TIM record found (978978)
	12:30:52 (465319)	5794	Vacuum TT20 (B): TRUE -> FALSE
	12:30:52 (465319)	5794	Vacuum TT20 (A): TRUE -> FALSE
	12:30:52 (449766)	5778	BPL record found (0xa)
	12:30:52 (449766)	5778	Vacuum LSS2 (B): TRUE -> FALSE
	12:30:52 (449766)	5778	Vacuum LSS2 (A): TRUE -> FALSE
	12:30:46 (670990)	10800	TIM record found (978977)
	12:30:35 (870987)	5999	TIM record found (978976)
	12:30:29 (870988)	10799	TIM record found (978975)
	12:30:19 (70998)	6000	TIM record found (978974)
	12:30:13 (70998)	10800	TIM record found (978973)
	12:30:02 (270996)	6000	TIM record found (978972)
	12:29:56 (270995)	10800	TIM record found (978971)
	12:29:49 (335249)	3864	BPL record found (0xf)
	12:29:49 (335154)	3864	BPL record found (0x3)
	12:29:45 (470993)	6000	TIM record found (978970)
	12:29:39 (470993)	10800	TIM record found (978969)
	12:29:28 (670990)	6000	TIM record found (978968)
	12:29:22 (670990)	10800	TIM record found (978967)
	12:29:11 (870988)	6000	TIM record found (978966)
	12:29:05 (870988)	10799	TIM record found (978965)
	12:28:55 (70998)	6000	TIM record found (978964)
	12:28:49 (70998)	10800	TIM record found (978963)
	12:28:38 (270996)	6000	TIM record found (978962)
	12:28:32 (270996)	10800	TIM record found (978961)
	12:28:21 (470993)	6000	TIM record found (978960)
	12:28:15 (470993)	10800	TIM record found (978959)

Figure 3 : BIC history buffer with the recording of the TT20 vacuum interlock.



FILTER... ☑ USE SNAPSHOT

A/B	TIME	DELTA	DESCRIPTION
	12:41:58 (670990)	10800	TIM record found (979057)
	12:41:47 (870988)	6000	TIM record found (979056)
	12:41:41 (870987)	10799	TIM record found (979055)
	12:41:31 (70998)	6000	TIM record found (979054)
	12:41:25 (70998)	10800	TIM record found (979053)
	12:41:14 (270996)	6000	TIM record found (979052)
	12:41:08 (270995)	10800	TIM record found (979051)
	12:40:57 (470992)	5999	TIM record found (979050)
	12:40:51 (470993)	10800	TIM record found (979049)
	12:40:40 (670990)	6000	TIM record found (979048)
	12:40:34 (670990)	10800	TIM record found (979047)
	12:40:23 (870987)	5999	TIM record found (979046)
	12:40:17 (870988)	10799	TIM record found (979045)
	12:40:07 (70998)	6000	TIM record found (979044)
	12:40:01 (70998)	10800	TIM record found (979043)
	12:39:50 (270995)	6000	TIM record found (979042)
	12:39:44 (270995)	10800	TIM record found (979041)
	12:39:37 (158693)	3687	Vacuum LSS2 (B): FALSE -> TRUE
	12:39:37 (158693)	3687	Vacuum LSS2 (A): FALSE -> TRUE
	12:39:37 (158688)	3687	Vacuum LSS2 (B): TRUE -> FALSE
	12:39:37 (158688)	3687	Vacuum LSS2 (A): TRUE -> FALSE
	12:39:37 (158541)	3687	Vacuum LSS2 (B): FALSE -> TRUE
	12:39:37 (158541)	3687	Vacuum LSS2 (A): FALSE -> TRUE
	12:39:37 (158536)	3687	Vacuum LSS2 (B): TRUE -> FALSE
	12:39:37 (158536)	3687	Vacuum LSS2 (A): TRUE -> FALSE
	12:39:37 (158527)	3687	Vacuum LSS2 (B): FALSE -> TRUE
	12:39:37 (158527)	3687	Vacuum LSS2 (A): FALSE -> TRUE
	12:39:33 (470993)	6000	TIM record found (979040)
	12:39:27 (470993)	10800	TIM record found (979039)
	12:39:16 (670991)	6000	TIM record found (979038)
	12:39:10 (670990)	10800	TIM record found (979037)
	12:38:59 (870988)	6000	TIM record found (979036)
	12:38:53 (870987)	10799	TIM record found (979035)
	12:38:43 (70999)	6000	TIM record found (979034)
	12:38:37 (70998)	10800	TIM record found (979033)
	12:38:26 (270996)	6000	TIM record found (979032)
	12:38:20 (270995)	10800	TIM record found (979031)
	12:38:09 (470992)	5999	TIM record found (979030)
	12:38:03 (470993)	10800	TIM record found (979029)
	12:37:52 (670990)	6000	TIM record found (979028)

Figure 4 : BIC history buffer with the recording of the vacuum interlock in LSS2.

HW Interlock Test Sheet

EQUIPMENT TYPE	Electrostatic separators (ZS), extraction bumpers, BLMs (LSS2 and TT20)
EVENT	Extraction bump at twice nominal setting
DATE	09.11.2007 11:19:04 and 11:19:24
ANALYSIS	J. Wenninger/ K. Cornelis

BEAM CONDITIONS

SPS CYCLE	SFT+LHCPILOT (20.4 s)
SPS TIMING USER	SFTPRO1
BEAM TYPE	FT
BEAM INTENSITY	9×10^{12} protons / 1 batch

Event description

On Friday November 9th 2007, a new configuration was tested for the slow extraction from the SPS. The new configuration does not require the ‘Q-split’ scheme that has been the baseline for slow extraction from the SPS for the last 20 years. Since the West Area was stopped the ‘Qsplit’ scheme has been kept although it was no longer required. The new scheme simplifies the powering of the SPS main quadrupoles.

In the afternoon of November 9th, the first of five electrostatic separator tanks (ZS1) used to extract the SPS fixed target beam started to spark at a rate of ~20-40 sparks per hour for beam intensities of ~2.0×10^{13} protons. The sparking was correlated to the beam presence (no sparking in the absence of beam) and could not be improved during the week-end of 10-11th November.

From the post-mortem analysis of the day that is summarized in this document, it is possible to reconstruct the event sequence that lead to the damage of ZS1.

Event analysis

As a preparation for the new extraction, the required ‘knobs’ underwent a final test in the evening of Thursday November 8th. It turned out that the knobs that were defined for the extraction bump (45 mm amplitude), the extraction sextupoles and the extraction septa did not work as expected. In fact the LSA trim engine did not apply them properly. This is probably due to the fact that at the time when the knobs were created (in July 2007) the knob creation application had a bug. Consequently new versions of each knob were defined. To be sure that the knobs would work the next day for the cycle on which the extraction would be tested, the old extraction knobs/trims were zeroed and replaced by the new knobs (trimmed to their nominal values). After the knob test, the new knob trims were zeroed again and the knobs for the existing extraction set back to their initial values. Unfortunately during that process the new extraction bump was left at its nominal setting, and therefore added to the existing extraction bump, thus effectively doubling the bump to 90 mm, well beyond the position of the ZS (68 mm). This was not detected as the extraction bumper magnets are so strong that it is indeed possible to introduce a very dangerous bump, with amplitudes well beyond the extraction requirements.

The next morning at **11:19:04** and **11:19:24 UTC** (12:19:04 and 12:19:24 local time, time of the cycle start), two consecutive extractions were attempted with beam intensities of **9×10^{12} protons** (1 injection from the PS). The beam was dumped by a **BLM interlock from LSS2/TT20** towards the end of the ramp, at **3941.28** and **3941.94 ms**. The precise timing of the beam dump is obtained from the BIC data logging. After the second extraction, the ZS system triggered a software interlock (high voltage system). The software interlock system (SIS) would have stopped the beam after 3 consecutive beam loss triggers. As will be shown later, this corresponds to the moment when the increasing extraction bump pushed the core of the beam close to/across the wires of the extraction septum.

The beam loss pattern in LSS2 and TT20 extracted from the logging DB for the first extraction with double extraction bump is shown in Figure 1. As can be seen, the losses in the extraction channel are not very different from the usual pattern. The loss on ZS1 (first bin) is rather ‘low’ compared to the typical value during extraction. The beam was dumped by BLM TT20.BLM.210222 that is installed near a horizontal aperture limitation. The loss largely exceeds the threshold because the TT20 BLMs (from TT20.BLM.210222) are of the BLRING type, with a sampling of 20 ms. **If BLM TT20.BLM.210222 had been of the BLD type (like the BLMs around the ZS, MST and MSE), the beam would have been dumped within few microseconds, and the damage may have been prevented.**

The superposition of the two extraction bumps leads to a bump amplitude growth of 0.3 mm/ms at the time of the event. At cycle time 3941 ms the bumps have reached 80% of their nominal value, which corresponds to a displacement of 72 mm, to be compared with the ZS upstream girder distance of 68 mm. A beam emittance measurement performed on Saturday 10th November yielded a rms beam size of ~0.76 mm at the ZS entrance. At a speed of 0.3 mm/ms, the beam would be swept over the septa wires in ~ 9 ms (assuming a beam of +- 4 sigma). Of course it is not possible from the loss data to know if the beam was dumped before or after the beam core crossed the wires. Analysis of the spark counts indicate that from the moment of those two extractions

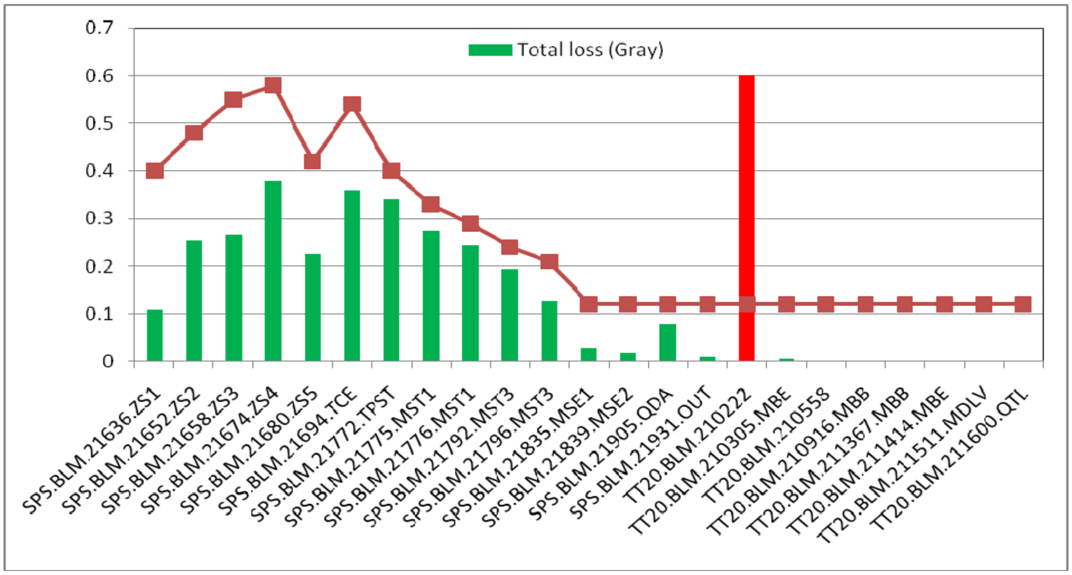


Figure 1 : Logged beam loss pattern in LSS2 and TT20 for the first extraction with double extraction bump. The curve indicates the BLM thresholds (all values in Gray). As can be seen, the losses in the extraction channel are not very different from the usual pattern. The loss on ZS1 (first bin) is 'low'. The beam was dumped by BLM TT20.BLM.210222 that is installed near a horizontal aperture limitation. The loss largely exceeds the threshold because the TT20 BLMs (from TT20.BLM.210222) are of the BLRING type, with a sampling of 20 ms.

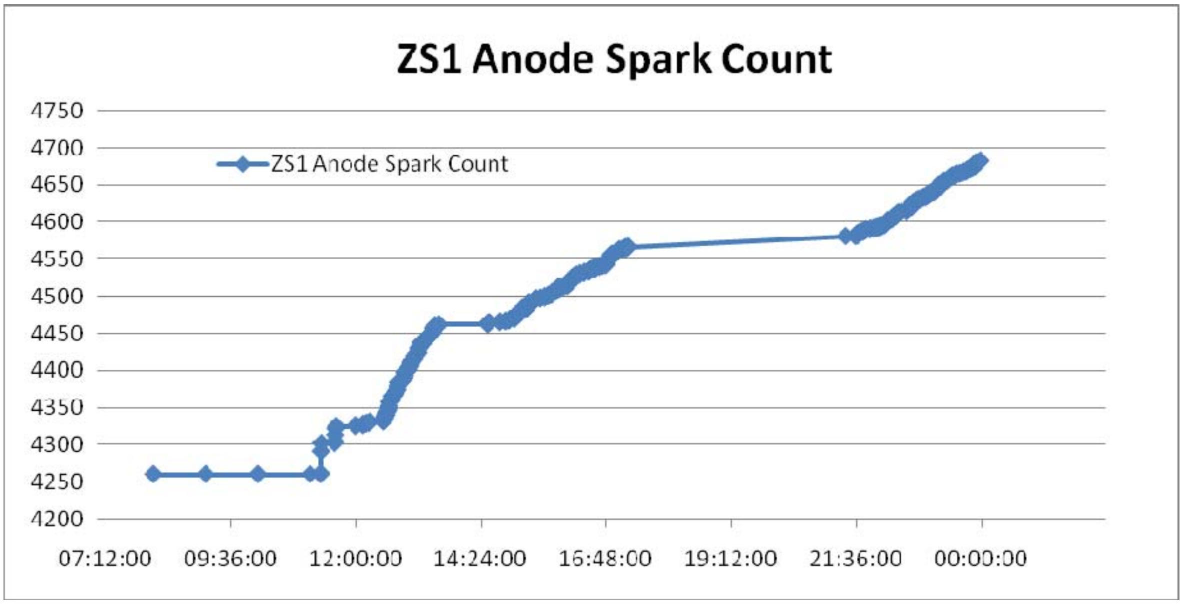


Figure 2 : Spark count rate of ZS1 on November 9th. Note that the time is in UTC (local time - 1 hour). One can clearly see the steep increase at 11:19, time of the incident. From that moment onwards, the ZS1 sparked as soon as beam was extracted from the SPS.

Setting up of the new slow extraction configuration continued smoothly during the afternoon of November 9th, and no problems were encountered except for ZS1 sparking. Steering of the TT20 went smoothly, and after some optics adjustments at the splitters, the beam spots on the targets T2, T4 and T6 seemed normal. Beam profiles in the extraction channel and on the splitters did not differ significantly from the 'Q-split' optics. The beam loss pattern was also identical within say 10% after some rough adjustment of the ZS and MST girders.

Recommendations for future improvements

The following recommendations can be made for the future, in particular in view of the very high peak intensities that will be extracted with the long flat top:

1. **BLM TT20.BLM.210222** will be connected to the LSS2 BLD system to reduce reaction times in case of failures, as this BLM is installed close to an aperture limitation. There is a free channel in the LSS2 BLD electronics that can be used without problems.
2. In the summer of 2007 a surveillance of the MST, MSE, MBE and splitter magnet currents has been implemented in SIS. The number of surveyed elements had unfortunately to be limited due to performance problems with the ROCS data server (mugef-server). If the bumper current had been surveyed by SIS, the incident could have been avoided. In 2008 the current of the bumpers will be added to the SIS surveillance, even if this will not improve the stability of the mugef-server.
3. A hardware interlock system to survey the PC currents similar to the one used for the fast extraction could be implemented a priori, but this requires:
    - Two cables and interconnection boxes (CIBUs) between the BA2 ROCS FEC and the BA2 BIC.
    - A new logic for the current surveillance, since the interlocks have to be connected to the beam dump kicker (and not to the fast extraction kicker like in LSS4 and LSS6). This implies that during LHC and CNGS cycles, a fake 'OK' has to be provided by the system. The same applies for the FT cycles during injection, ramp and beam-out.